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Subject: Structural Engineering

Keywords: Damping
Shear
Structure
Vibrations

Publication Date: 2004

Original Publication: CTBUH 2004 Seoul Conference

Paper Type:
1. Book chapter/Part chapter
2. Journal paper
3. **Conference proceeding**
4. Unpublished conference paper
5. Magazine article
6. Unpublished

Experimental Assessment of Floor Vibration Using iTECH Composite Beam

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Abstract

The story height of the tall buildings is the significant factor due to the limited construction area within the central city such as Seoul. Authors developed a composite beam which uses asymmetric steel section with web openings. The structural performances for shear, moment were tested. Since the top flange of the proposed beam is within the slab, the vibration characteristics have to be verified by the test.

In this paper, the vibration performance of the proposed composite slab was explored by the series of test. The fundamental period and damping were measured at each step such as steel erection stage, concrete casting stage, and finishing stage. Four types of boundary conditions are also considered. The test results are compared with that of the code. As a result, the proposed composite floor showed enough vibration characteristics.

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Keywords: iTECH, natural frequency, damping ratio, floor vibration

1. Introduction

Composite beams with decks are mostly used in steel structures since these require simple construction and fewer man-hours, and need no formwork. Furthermore, they have good constructional workability[26, 34]. However the composite beam also has several disadvantages. First, the upper flange of its steel section does not produce structural capacity in the positive moment region so that it can be reduced at that region. Second, its shear stud has to be set up in situ on top of the upper flange, and the fireproofing material must cover the exposed steel surface[21, 33]. Thus, high-rise residential buildings need different types of beams with lower story depth. Since the height of a story is a significant factor in residential buildings, this is especially critical in restricted city areas. Moreover, environmentalism is a growing issue, and fireproofing of the steel part has to be reduced or eliminated. After the collapse of the World Trade Center in New York, reliable fireproofing has become a significant factor for residential buildings.

A great number of researchers and engineers are eager to find the best solution for the composite beam.

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One such solution proposed is the slim floor, which was developed to minimize story height[28, 29, 30, 31, 32]. It is now widely used in Europe including England and Finland. As shown in Fig. 1, the general form of this structural system consists of fabricated steel beams and a deep deck. Since the concrete is cast in situ between the upper flange and the bottom flange, the slim floor gives about an hour to an hour and a half of fireproofing. However, the beam-column is connected with pin connection and is not suitable for moment resisting frames that are widely used in Korea. Therefore, the use of the slim floor for the construction of high-rise buildings is not practical.

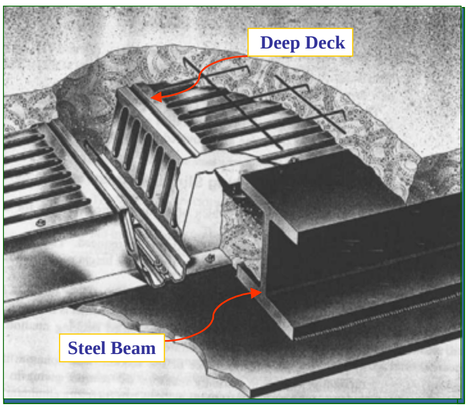


Fig.1 Slim floor [22)]

In North America, the girder-slab (Fig. 2) is used for the lower-story composite beam system[23]. The general form of this system consists of fabricated asymmetrical steel beams with a web opening called D-section and a deep hollow core precast plank. Since the precast slab is placed at the bottom flange of the D-section, constructional workability is acceptable. However, the beam-column is also connected with pin connection and is not suitable for moment resisting frames.

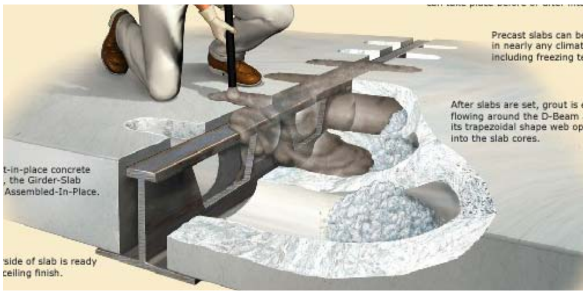
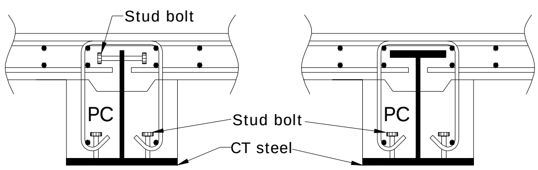


Fig. 2 Girder-slab system [11]

As shown in Fig.3 (a), researchers developed the TEC (Technical, Economical, and Convenient) beam, which consists of structural tee, precast concrete in factory, and in situ concrete slab. The structural performance of the TEC beam was experimentally assessed[21] and was evaluated to be good. However, the construction cost is not practical due to precast concrete, delivery cost, and shoring. To construct a non-shoring beam, A-TEC (Asymmetric TEC Beam) beam shown in Fig.3 (b) was developed from the TEC beam[24]. The A-TEC beam showed enough structural capacity but still had the disadvantages of precast concrete. It also showed slippage between concrete and steel because no studs are provided.



(a) TEC beam (b) A_TEC beam

Fig. 3. Composite floor systems proposed by the authors.

To make the story height less, a newly developed composite beam is proposed by the authors. It is named the Innovative, Technical, Economical, and Convenient Hybrid (abbreviated as iTECH) system. The structural performance in terms of strength design, were proved by the experimental and analytical researches. Since the depth of the iTECH system is reduced less than classical steel composite beam, the serviceability design is questionable.

When issues of serviceability with regard to floor vibration were investigated, it is required to find the natural frequency and damping ratio of floor. Furthermore, it is recommended to analyze the influence of the structural and non-structural members on frequency and damping ratio through field experimentation at each construction stage; (1) steel erection stage, (2) concrete casting stage, and (3) finishing stage. Since there are no reliable Korean standards for serviceability design, the evaluation of serviceability of the proposed composite beam was verified by the three foreign codes such as Japan, ISO, and DIN.

In this study, the vibration characteristics of the proposed composite beam were tested at each construction stage. The serviceability responses are evaluated according to JIS, ISO, and DIN.

2. Concept of iTECH System

The iTECH system has an asymmetric steel assembly with web openings, where the top plate is welded on top of inverted structural tees cut as “honeycomb” style (Fig.4). The steel assembly is fabricated in the factory. Both sides of the web and the slab are filled with in situ concrete. The iTECH system showed good constructability that is similar to that of steel construction. The C-channel is placed on top of the bottom flange at the shop and supports the deck during the construction stage; it is not a structural member. The web with the opening integrates the concrete beam and the asymmetric steel, giving rise to the composite action.

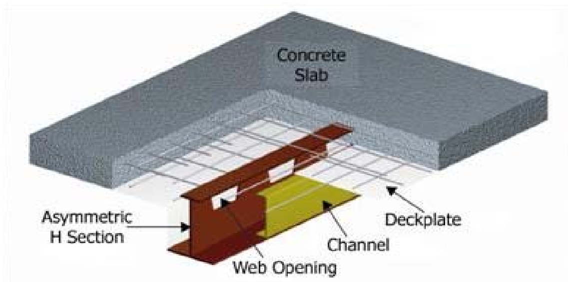
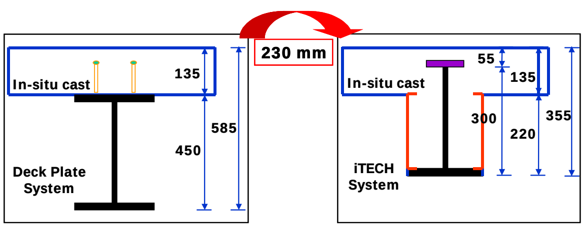


Fig.4. Concept of iTECH System



a) Steel composite beam b) iTECH System

Fig.5. Comparison of classical steel composite beam with iTECH System

Through bonding and bearing between the web concrete and steel, iTECH behaves as a composite part without the mechanical shear stud. The advantages of the iTECH system include: (1) lower construction cost compared to reinforced concrete or steel frame structures; (2) shorter construction time compared to the reinforced concrete structure; (3) better construction quality control and construction management; (4) flexibility in planning; and (5) lower story height due to shallower beam depth. Fig.5 shows that use of the iTECH system can reduce beam depth to 355mm from 588mm for a normal steel composite beam.

3. Vibration Test

3.1 Test building

Two-story buildings, built with iTECH composite beam, have been used to test effects of vibration. The test was performed on the 2nd and roof floor. Here, the floor is constructed with iTECH composite beams and 4-bay 3.9m x 6.9m deck slabs, using SC (steel concrete) columns.

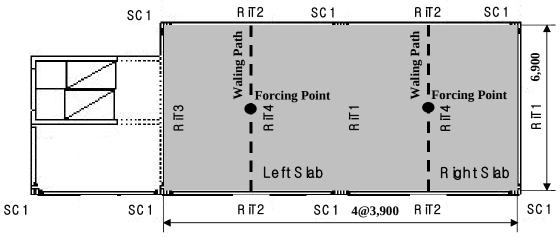
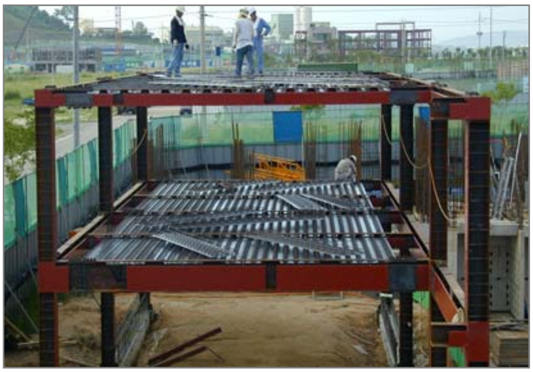


Fig.6. Roof floor plan

Fig. 6 shows the roof floor plan of the test building. The colored areas are the experimental areas. Experimentation was performed in the center of the slabs. Fig.7 shows each construction step of the pilot building. Vibration tests are commonly performed to test the floor at concrete casting stage[3, 4, 5]. In this study, three different construction stages were considered to take into account the changes in dynamic characteristics during the construction. Fig.8 illustrates a schematic section of the iTECH system. The thickness of the channel on the bottom flange is 2mm. The other factors have changed according to the design parameters. Fig. 9 illustrates a material section of the iTECH system as applied to the pilot building and Table 1 lists the size of the each iTECH section. Here, IT represents the factory-produced, hot rolled steel beam section.

Table 1. The size of the iTECH section

	IT-D×B_b×T_b×T_w	Location
beam	IT-305×300×11×18	2IT1, 2IT2, 2IT3, RIT1-RIT4
	IT-555×300×13×20	2IT1, 2IT4
column	H-310×305×15×20	SC1



a) Steel erection stage

b) Concrete casting stage

c) Finishing stage

Fig.7. Picture at each construction step

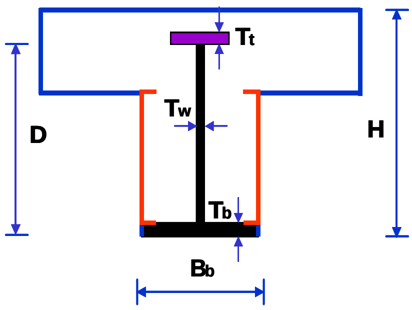
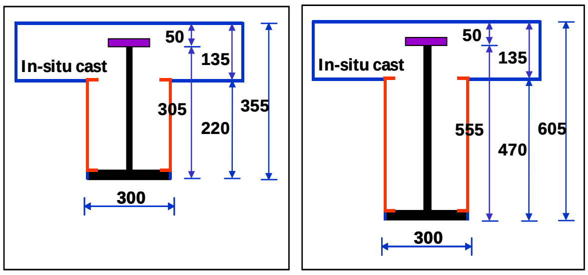


Fig.8. Section size of the iTECH System



a) IT-305×300×11×18 b) IT-555×300×13×20

Fig.9. Section of iTECH system used

3.2 Experiment Schedule

Figs.10 and 11 show the measurement equipment and the measurement system, respectively. There were two kinds of vibration source considered in this experiment-impact load and walking load-each tested in two ways. Impact load was tested using a sand drop and a heel drop, both analyzed in terms of natural frequency and damping ratio.

Fig.10. Measurement equipment

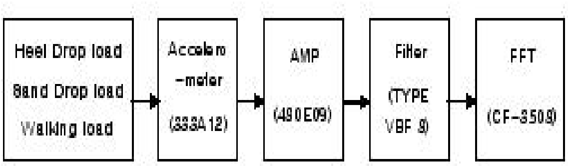


Fig.11. Map of measurement system.

Measurements of floor acceleration which were made with a one and two-person walking load, were used to evaluate serviceability of the floor. To analyze dynamic characteristics of the system, this testing was conducted at each of the three construction stages: steel erection stage, concrete casting stage, and finishing stage. Table 2 provides details of each construction step. Sensors were placed at the weakest point of each slab, the center, to record dynamic characteristics.

Fig.12 (a) shows the impact load experiment. For the sand drop impact, a 30kg sand bag was dropped from 50cm high. The heel drop test measured the impact of the heel dropping from 5cm high. This process was then repeated three times and experimental results were averaged across trials. Fig.12 (b) illustrates the walking load experiment, where one 70kg person with a stride of 75cm walks back and forth 30cm off the sensor at a speed of 1.5m/sec and a frequency of 2Hz.

a) Impact load b) Walking load

Fig.12. iTECH System Concept

Table 2. Construction step

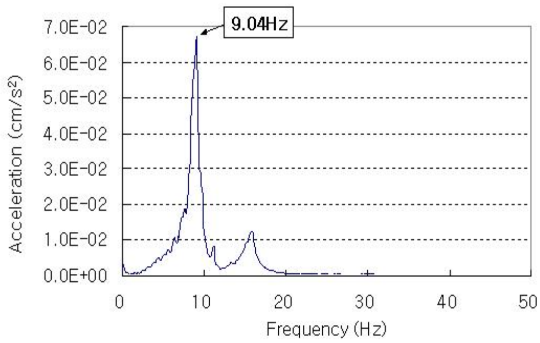
Construction step		Components
Step 1	steel erection stage	iTECH beam + deck plate
Step 2	concrete casting stage	Step 1 + concrete casting
Step 3	finishing stage	Step 2 + exterior wall + partition wall + ceiling + finishing

4. Test Results

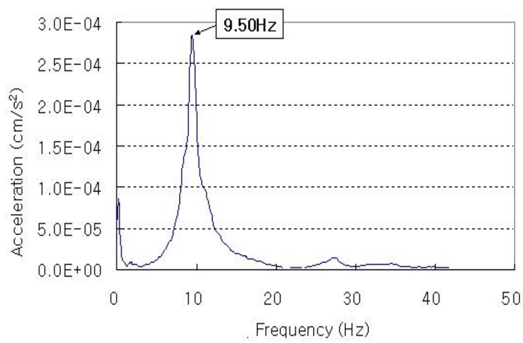
4.1 Frequency

The natural frequency of the slab using the iTECH composite beam system was found through the slab-vibration experiments. Fig.13 shows the power spectrum for each construction stage in terms of a time history during the heel drop impact on the left slab of the roof story. Table 3 lists the natural frequency of the floor under the impact loads, including the sand drop and heel drop loads. As the construction goes, the corresponding natural frequency increases.

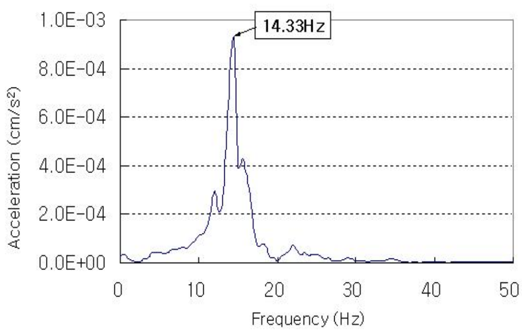
Fig.14 is an expression of Table 3 in a graph format. The graph describes the rate of vibration of the iTECH composite beam at each construction step. In comparing the construction steps, the frequency increases slightly to 2.9% on average from the steel erection stage to concrete casting stage. The reason for this small increase in frequency is that both the mass and the stiffness of the structure were increased. By contrast, the natural frequency increases dramatically to 49% at the finishing stage because of the finishing material and the addition of walls.



a) Steel erection stage



b) Concrete casting stage

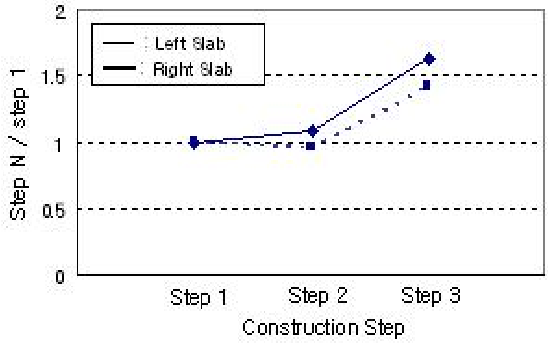


c) Finishing stage

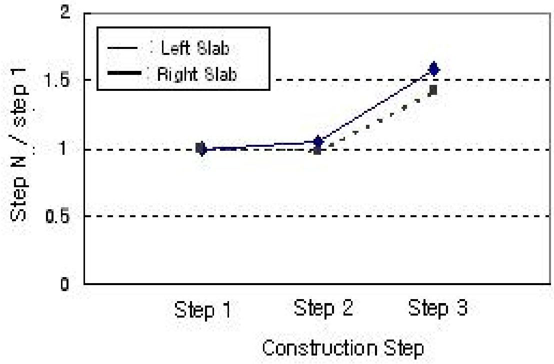
Fig.13. Response at each stage

Table 3. Natural frequency under the impact loads (Hz)

construction step	floor	sand drop		heel drop		Error (%)	
		Left	Right	Left	Right	Left	Right
steel erection stage	roof	8.83	8.54	9.04	8.58	2.4	0.5
concrete casting stage	2nd	12.00	11.25	12.00	11.25	0	0
	Roof	9.50	8.50	9.50	8.50	0	0
finishing stage	2nd	15.75	17.50	16.00	17.75	1.6	1.4
	roof	14.33	12.50	14.33	12.50	0	0



a) Sand drop load



b) Heel drop load

Fig. 14. Response of different method at construction step

4.2 Damping

Damping was calculated using equation (1) and the amplitude was calculated as shown in Fig.15.

$$\xi = \frac{1}{2\pi n}\ln\frac{x_1}{x_{i+2n}}\times 100 \qquad (1)$$

in which, ξ is damping ratio, *n* is natural frequency, and x_i is the amplitude of wave at each half period

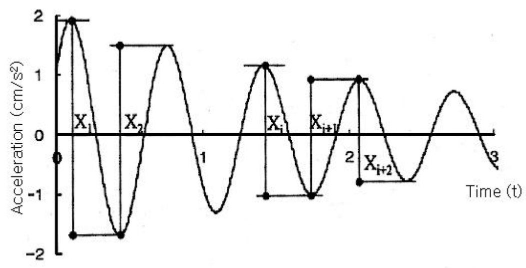
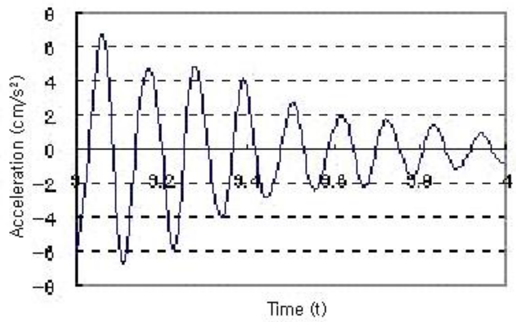


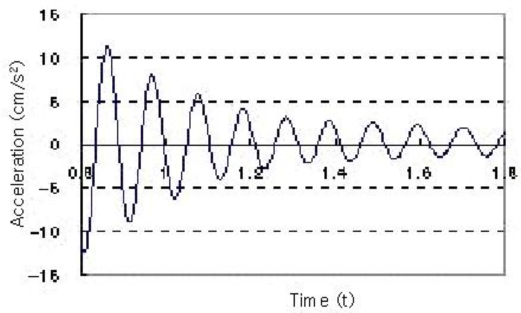
Fig.15. Estimation of damping

Fig 16 shows damping at each construction stage. Table 4 shows damping ratio with regard to the impact loads, which includes the sand drop load and heel drop load.

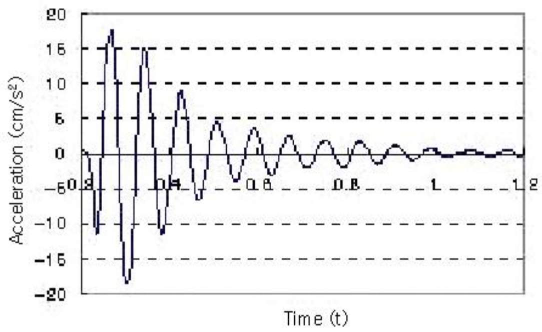
After completing the building using iTECH composite beams, the damping of 6.9% in the second floor and 7.3% in the roof floor is 2-5% higher than classical steel system buildings.



a) Steel erection stage



b) Concrete casting stage



c) Finishing stage

Fig.16. Damping at each construction stage

Table 4. The damping about the impact loads

construction step	floor	sand drop		heel drop		error (%)	
		Left	Right	Left	Right	Left	Right
steel erection stage	roof	NA*	NA*	4.07	NA*	NA*	NA*
concrete casting stage	2nd	2.68	3.17	2.26	3.11	18.6	1.9
	Roof	4.54	NA*	4.20	3.62	8.1	NA*
finishing stage	2nd	6.71	NA*	6.99	NA*	4.2	NA*
	Roof	7.19	8.13	7.37	6.50	2.5	25.1

5. Evaluation of Serviceability

5.1 Applied Codes

The serviceability of the iTECH system has been evaluated according to the Japanese Code[6)], ISO 2631-2[9)] and DIN 4150[10)]. In Korea, these three foreign serviceability codes are commonly used to evaluate vertical vibration of floor. The evaluation parameters defined by each code is as follows:

(1) Japanese Code: JIS (1991)

Normally, natural frequency of floor ranges from 3Hz to 30Hz. Since there is no specific standard for general shops, the pilot building in the current research have been classified as V-5 and evaluated as general office.

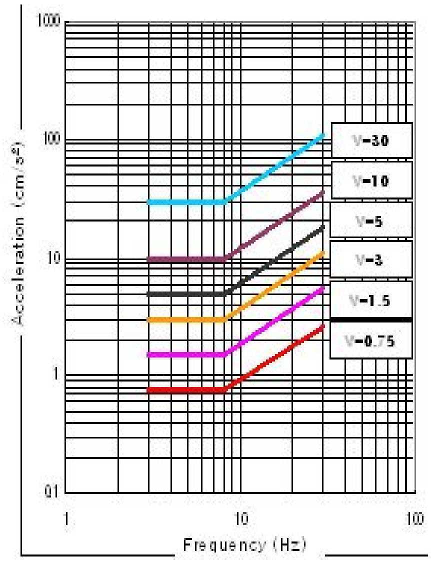


Fig.17. The Architecture Institute of Japan code (1999)

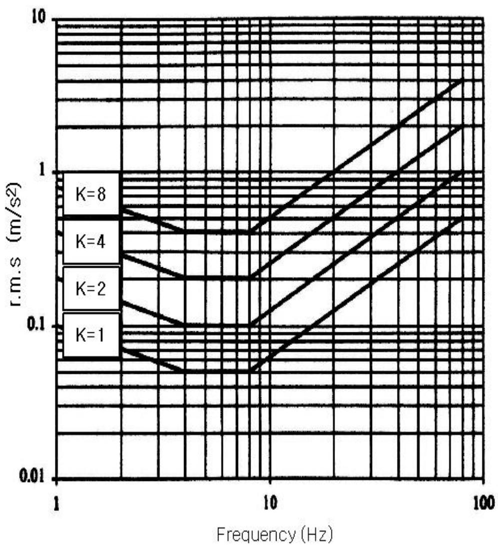


Fig.18. ISO 2631-2 code (1989)

(2) ISO 2631-2(1989)

Natural frequency of floor ranges from 1Hz to 80Hz, represented in Fig.18 by a curved line. Here, given coefficient K, K4 has been established for office.

(3) DIN 4150(1986)

The natural frequency of floor ranges from 1Hz to 80Hz. In the case of continuing vibration in a commercial area, the slabs have been rated for a KB of 0.4 during the daytime and 0.3 at the night. The KB is calculated as follows;

$$KB : d\frac{0.8f^2}{\sqrt{1+0.032f^2}} \tag{2}$$

$$d = \frac{v}{2\pi f} = \frac{a}{2\pi^2 f^2} \tag{3}$$

in which d, f, a are the displacement response, the natural frequency, and the acceleration response, respectively.

The details are listed in Table 5.

Table 5. Allowable KB values (DIN4150)

Zone	Time	Allowable KB value	
		Continuous vibration	Impact vibration
Resident, Suburban zone	Day	0.2(0.15*)	4
	Night	0.15(0.1*)	0.15
Large city, Mixed zone	Day	0.3(0.2*)	8
	Night	0.2	0.02
Commercial zone	Day	0.4	12
	Night	0.3	0.3
Industrial zone	Day	0.6	12
	Night	0.4	0.4
Special zone	Day	0.1 ~ 0.6	4 ~ 12
	Night	0.01 ~ 0.4	0.15 ~ 0.4

* Applicable for 5Hz or below

5.2 Evaluation Results

The frequency of the second floor was 15.88Hz in the left slab and 17.63Hz in the right slab. After three repetitions of the experiment, accelerations were $0.73cm/s^2$ ~ $2.54cm/s^2$ under the one-person walking load and $2.38cm/s^2$ ~ $4.02cm/s^2$ under the two-person walking load.

The frequency of the roof floor was 14.33Hz in the left slab and 12.50Hz in the right slab. After three repetitions of the experiment, accelerations were $1.53cm/s^2$ ~ $1.54cm/s^2$ under the one-person walking load and $2.06cm/s^2$ ~ $2.52cm/s^2$ under the two-person walking load.

As illustrated in Fig. 19, these results were within the parameters of all three of the codes used to evaluate serviceability of the pilot buildings.

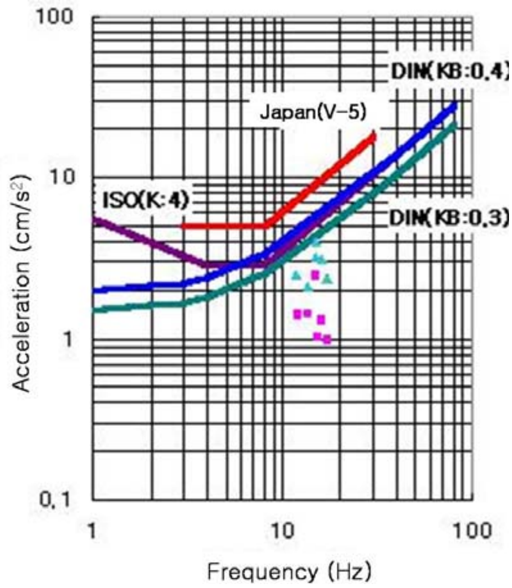


Fig.19. The serviceability evaluation

6. Conclusion

Dynamic characteristics of the iTECH composite beam system were obtained by sand and heel drop experiments. The natural frequency and damping ratio at each construction stage were found and the serviceability of the proposed composite beam was evaluated in terms of acceleration response under the one- and two- person walking load. The findings could be summarized as follows;

1) In comparing each construction step, the frequency increased slightly to 2.9% on average, from the steel erection stage to concrete casting stage. The reason for this small increase in frequency is that both the mass and stiffness increased together. In contrast, the natural frequency increased dramatically to 49.0% at the finishing stage because of increased mass due to the finishing material and walls.

2) After completing the building using iTECH composite beam, the second floor and roof showed damping of 6.9% and 7.3% respectively. This is relatively higher than in a classical steel system buildings which has damping of 2~5%.

3) With regard to serviceability, the performance of test building satisfied defined criteria of three different national codes showing no problems in this area.

Acknowledgement

The authors express their sincere gratitude to the concerned people of Haesong Kigong, Jeil Deck, and Daewon Construction, for the sustainable support.

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